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THESIS

AIR ASSET TO MISSION ASSIGNMENT FOR DYNAMIC HIGH-THREAT ENVIRONMENTS IN REAL-TIME

by

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March 2015

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ABSTRACT

This thesis develops pre-processing algorithms and a mixed integer programming model that solves the route selection and asset-to-mission assignment problem in the presence of threat air-defense systems. Our model and algorithms reduce the planning timeline and coordination burden by handling the heavy computational aspects of the planning process. It takes as input current aircraft, target, and threat information and produces asset-to-mission pairing recommendations that accomplish the mission while providing routes and coordination to reduce the risk from threats by avoiding surface-to-air threats, when possible, or by adding suppression assets, if available. The resulting recommendations are created significantly faster and more reliably than can be done by existing integrated fires methods.

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List of Acronyms and Abbreviations

AD	air defense
AOC	air operations center
AOD	air operations directive
AOR	area of responsibility
ATFLIR	Advanced Targeting Forward Looking Infrared
ATO	air tasking order
C2	command and control
CONOPS	concept of operations
DARPA	Defense Advanced Research Projects Agency
DT	dynamic targeting
GAMS	General Algebraic Modeling Software
GUI	graphical user interface
HARM	high-speed antiradiation missile
ISR	intelligence, surveillance, and reconnaissance
JDAM	Joint Direct Attack Munition
JFACC	joint force air component commander
JFC	joint force commander
JFIRE	Joint Applications of Firepower
JIPTL	joint integrated prioritized target list
JP	joint publication

JTIDS Joint Tactical Information Distribution System

LGB laser-guided bomb

MAAP master air attack plan

MIP mixed-integer programming

MISREP mission report

NSAWC Naval Strike and Air Warfare Center

RAPT-OR Rapid Asset Pairing Tool-Operations Research

RASP Rapid Air Strike Pairing

SAM surface-to-air missile

SEAD suppression of enemy air defenses

TST time-sensitive target

US United States

WEZ weapon engagement zone

Executive Summary

The task of managing large-scale integrated fires in a static combat environment is complicated. Command and control (C2) operators must balance available asset capabilities against mission requirements to achieve objectives efficiently within their designated area of responsibility (AOR). While this task is a complex one in a static environment with a fixed number of assets and missions, it is further complicated when available assets and missions are dynamic.

Virtually all combat air asset-to-mission assignments involving United States (US) forces in the last 10 years have occured in environments where the enemy has had limited-to-no air defense (AD) capability, such as integrated surface-to-air missiles (SAMs). Proliferation of capable AD systems with integrated, mobile, and often overlapping SAM weapon engagement zones (WEZs) has increased the demand for mitigation measures. The primary means of mitigating AD threats are avoidance and suppression. The ability to rapidly correlate threat information and implement mitigation measures in real-time does not exist for these high-threat environments. Instead, planners execute a dedicated planning process over the course of several hours. This means that the short windows of opportunity for time-sensitive target (TST) missions are often lost.

Military air mission planners, when confronted with the complexity of a high-threat environment with integrated threat AD systems, dedicate multiple hours balancing risk against mission accomplishment to develop a coordinated large-force strike package effort in order to accomplish their assigned mission to fight their way into and out of the target area. Planning for these missions begins with an inital set of mission assignments that is developed by the strike lead and then modified to account for risks from both enemy air-to-air and surface-to-air defenses, as well as to account for the probability for mission success, by selecting the most effective weapon-to-target pairings available.

We develop a set of algorithms and a mixed-integer programming (MIP) model that encapsulates the essential elements of the air mission planning process that lend themselves to automation and aid in the real-time assignment of assets to missions in the presence of enemy SAM threats. Our model takes in static data (lookup tables for aircraft survivability

and weapon performance) as well as dynamic data (locations of aircraft, targets, and threats as well as their capabilities and restrictions) to produce assignment recommendations that reduce risk to the force and increase the probability of mission success in a fraction of the time of existing methods. We propose algorithms that process the data, select an intial feasible set of pairing assignments, determine the risk reduced routing, from these routings determine which pairings require suppression along the route, and calculate routes for any suppression of enemy air defenses (SEAD) element flights which can feasibly join together to accomplish the mission. The result of these algorithms is a feasible set of pairing assignments. Once this is completed a reward value is calculated for each pairing and the optimal set of pairings is selected through a MIP problem.

In a simple test scenario of five aircraft and three targets, the model produces a recommendation and a visual chart of the routes in under 3 seconds. A larger scenario involving 35 aircraft and 18 targets solves in just over two minutes. The solutions are reliable and repeatable and are achieved in a fraction of the time that manual operators would take.

Implementation of this model can provide more efficient and effective use of aircraft. We recommend that C2 operators retain the role as the final decision maker in this process, validating the recommendations provided by the model and updating model parameters to ensure high-quality solutions throughout the planning process. C2 operators are provided a higher fidelity of information with the model. Future work on the model could extend its use to unmanned systems providing a decision making roles in distributed force environments.

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CHAPTER 1:
Introduction

1.1 Purpose and Overview

The task of managing large-scale integrated fires in a static combat environment is complicated. Command and control (C2) operators must balance available asset capabilities against mission requirements to achieve objectives efficiently within their designated area of responsibility (AOR). Large-scale integrated-fires management is further complicated when available assets and missions are dynamic. Overcoming systemic inefficiencies in existing integrated-fires planning requires automated decision aids that simplify computationally heavy tasks and put operators "on the loop" (Palmieri 2014).

Virtually all combat air asset-to-mission assignments involving United States (US) forces in the last 10 years have occured in environments where the enemy has had a limited surface-to-air missile (SAM) air defense (AD) capability. Proliferation of capable AD systems with integrated, mobile, and often overlapping weapon engagement zones (WEZs) has increased the demand for mitigation measures. The primary means of mitigating AD threats are avoidance and suppression. The ability to rapidly incorporate threat information and implement mitigation measures in real-time does not currently exist for high-threat environments. Instead, planners must execute a dedicated planning process over the course of several hours. This means that the short windows of opportunity for time-sensitive target (TST) missions are almost certain to be lost.

We propose a solution to this problem through the use of fast pre-processing algorithms and a mixed-integer programming (MIP) optimization model to produce recommendations for the C2 operator's approval; the alogrithms and model replicate and automate the decision making processes used in dedicated air mission planning. Pre-processing includes the development of routes with minimal risk from enemy AD systems making this solution useful in any threat environment. The final step of the pre-processing algorithms is to assign values to each feasible pairing of aircraft and weapon loadouts to missions. The MIP takes the values of the feasible set of asset-to-mission assignments as input and returns the

optimal selection of these assignments as recommendations to the operator. These results are faster and more reliable than current manual processes.

1.2 Problem Statement

"Standby," is too common a response from C2 operators upon airborne check-in for mission assignment in complex combat environments. This simple radio call indicates that the controller is task saturated; his proverbial "bucket" is full. The new flight of aircraft must wait, burning precious fuel, until the controller can process additional information. While this delay is wasteful, it has the potential to result in a missed opportunity if the controller is trying to pair up the assets under his/her current control for a mission that could be performed more effectively by the flight currently trying to check-in.

In the existing process, C2 operators rely on their knowledge and experience to assign assets to missions, however, research has demonstrated that even the most proficient operator's performance degrades when workload increases (Soller and Morrison 2008). Additionally, each possible assignment requires dedicated focus and computationally intensive steps in order to process available options and arrive at a decision. C2 operators often have other missions competing for attention and in order to speed up the mission assignments, a "best guess" is often used instead of a calculated comparison of alternatives. The quality of assignments are dependent largely upon the individual experience and skill of the operator and complex situations can result in inconsistent, and even ineffective, use of aircraft.

A crucial component of assigning air assets to missions is mitigating the risk to aircraft both en route to and in the conduct of the assigned mission. Currently, mitigation of threats is executed through the use of rudimentary rules-of-thumb for known threat locations. However, a newly detected SAM has the potential to invalidate all current assignments. In a situation such as this, the controller may need to either re-assign or cancel each mission in the AOR.

In a complicated threat environment C2 nodes must not hinder the accomplishment of theatre missions and objectives. There is a widening gap between technology advances that allow assets to operate in a distributed manner and our ability to adequately assign them to missions; we need a system of tactical decision aids to better inform the asset-to-mission assignment process at the operational level of war. We propose a model and accompanying

data processing algorithms to reduce the task loading of C2 operators, whereby the response to airborne assets checking in is nearly immediate assignment to an available mission that best uses the asset's capabilities to accomplishing theatre objectives.

1.3 Thesis Organization

Chapter 2 discusses of the intricacies of pairing airborne assets to available theatre missions and how C2 operators currently weigh the differences between multiple options. Chapter 3 describes the routing algorithm and MIP optimization model used to automate the asset-to-mission pairing process. Chapter 4 provides computational results against two notional scenarios. Chapter 5 presents conclusions and recommendations for advancement of the model and further applications.

1.4 Background of Asset-to-Mission Pairing Optimization

Dolan (1993) and Crawford (1994) develop models to automate and optimize the air tasking order (ATO) development, specifically with regards to where air assets should be assigned from and, if there were not enough air assets, which targets would be left unassigned. Dolan (1993) focuses on applications of the model for Naval War College wargame enhancement. While Crawford (1994) discusses a follow-on model that was designed for planners at the air operations center (AOC) and included incorporation of time and distance parameters to enable optimization across more than just a 24 hour period. Both of these works consider a static environment in which planners produce pairings well in advance of the actual execution.

Castro (2002) develops an optimization tool to aid in handling changes to the ATO from pop-up time-sensitive targets (TSTs). Weaver (2004) continues the development of the model and evaluates results from testing done using the model with USMC tactical aircraft. While this model performed well under the test conditions, further research determined that the speed of the model needed improvement.

The primary goal of follow-on research by Zacherl (2006), is to speed up the processing time of the model and tailor it to the specific needs of the planners who develop and process changes to the ATOs within the AOC. This research resulted in the creation of the Rapid Asset Pairing Tool-Operations Research (RAPT-OR) model. While this model sought to

answer the problem at the AOC level, McLemore (2010) modifies the model to provide C2 operators a higher fidelity automated decision aid.

One shortcoming of the prior work is that, if routing and timing considerations were taken into account at all, the distances flown were calculated as great-circle, or direct, routes due to the lack of detailed routing algorithms of appropriate fidelity and speed. While this is a useful simplifying assumption for areas where there are minimal obstructions to the route, direct routing is inadequate in a dynamic battlespace environments with high-threat AD systems.

Carlyle, Royset, and Wood (2008) use Langrangian relaxation to find near-optimal paths and enumeration techniques to close the optimality gap for constrained shortest-path problems, which significantly reduced the solve time required. Karczewski (2007) expounded upon this model through a 3-dimensional routing application for aircraft in order to minimize the risk from known threat AD systems. Other work in this area follows a similar format where a single aircraft, or group of aircraft, is pitted against a robust AD network (Berger et al. 2012, Lee 1995, Puustinen 2013, Royset et al. 2009, Zabarankin et al. 2006). While this consumate effort signifies admirable advancement of optimal routing efforts, the solve time remains a problem when computing thousands of possible routes.

We do not formulate and solve a constrained-shortest path problem; rather, our side constraint of available on-station time, or "playtime," will be used simply as a filter for feasibility on the minimum-risk routes. Our goal is to produce results for real-time decision-making processes which take into account routing considerations for multiple air assets and targets in the presence of threat AD systems. In order to achieve this task, routing solutions must be calculated using extremely fast algorithms.

1.5 Terms and Definitions

For this thesis, the following definitions are offered for the sake of clarity:

Flight — A specified group of aircraft (usually of the same type) which are coordinated in effort toward a common mission. Coordination is usually done through visual formations and therefore the aircraft are referenced under a common callsign designation.

Mission	For the purposes of this thesis, this term is synonymous with "target." joint publications (JPs) define this as, "the task, together with the purpose, that clearly indicates the action to be taken and the reason therefore" (JCS 2011).
Assignment	A pairing of a flight to a mission.
Low-threat	An environment where there are virtually no enemy SAM threat systems.
Medium-threat	An environment where a few enemy SAM threat systems operate independently of each other.
High-threat	A dense environment of coordinated enemy SAM threat systems within an integrated air defense network.

1.6 Scope and Limitations

This thesis develops a model which is intended to produce recommendations in both assignments and routing, in the presence of enemy SAMs, to inform decisions at the operational level of war in real-time. Additionally, this same model could be used to support analysis on a broader scale, such as within the AOC, to help inform decisions of which assets will be sent to particular AORs with the confidence that the C2 operator within that AOR will assign those assets as forseen by the higher command, given the same operational picture. Additionally, multiple runs of the model can provide an analysis-of-alternatives at the AOC level for allocation and planning purposes.

The input data for the model contains both static information, such as weapon effectiveness lookup tables, and dynamic information, like real-time position and capabilities for assets as well as target and threat information. The static tables allow intelligence inputs from specific performance data of weapon, and weapon systems, to their respective target, or mission, as well as individual survivability data of aircraft types against known threat types. This information is used to enhance the fidelity of the assignment recommendations. Currently, a C2 operator would enter the dynamic information into a graphical user interface (GUI) as updates to assets, missions, and threats arrive which means that some of the information is likely to be slightly delayed. Future integration into digital data links, such as Joint Tactical Information Distribution System (JTIDS) or Link-16, could reduce such

time-latency. We use unclassified, notional values for the data, yet all of our models and algorithms can be easily adapted to any classified version of these tables.

The model results include route recommendations that are indicative of relatively safe routing from any SAM threats encountered en route, however, the C2 operator must still perform deconfliction between aircraft. The routing algorithm, as presented here, looks only at 2-dimensional routing and does not account for altitudes of the aircraft. Future adaptations of our model could account for deconfliction routing through the use of 3-dimensional overlay grids (processed to remove nodes that conflict with terrain), however, the added development time outweighed the utility of adding it into the model at this point.

CHAPTER 2:
Airborne Asset-to-Mission Pairing in High-Threat Environments

2.1 Introduction

Joint targeting is described as “the process of selecting and prioritizing targets and matching the appropriate response to them, considering operational requirements and capabilities" (JCS 2014). An important part of the process is the production of the air tasking order (ATO), which assigns flights and missions. This chapter describes the process as it relates to the development of the ATO and dynamic targeting assignments. Further, this chapter looks at the dedicated air mission planning process which accounts for enemy air defense (AD) threats. Through analysis of this crisis action planning we determine steps in the planning that can be automated to enable assignment decisions for time-sensitive targets (TSTs) that are more robust to dynamic SAM threats.

Previous research has looked at the allocation of airborne assets in support of missions which the joint force commander (JFC) has designated via the ATO as well as the shortened decision making process of the command and control (C2) operators in the real-time assignment of air-assets to dynamic targeting (DT) priority missions. The essential elements of those discussions are included as necessary, however, the reader should refer to Zacherl (2006) for an in-depth discussion of the air operations center (AOC) development of dynamic modifications to the ATO and to McLemore (2010) for an in-depth discussion of real-time mission assignments in low and medium-threat environments.

2.2 ATO Development

The ultimate authority for assigning air assets to missions resides with the JFC who can delegate the authority to the joint force air component commander (JFACC). The JFACC commands the AOC where subject matter experts plan against primarily static targets to organize coordinated actions of air assets toward the accomplishments of the JFC intent and concept of operations (CONOPS) (JCS 2014).

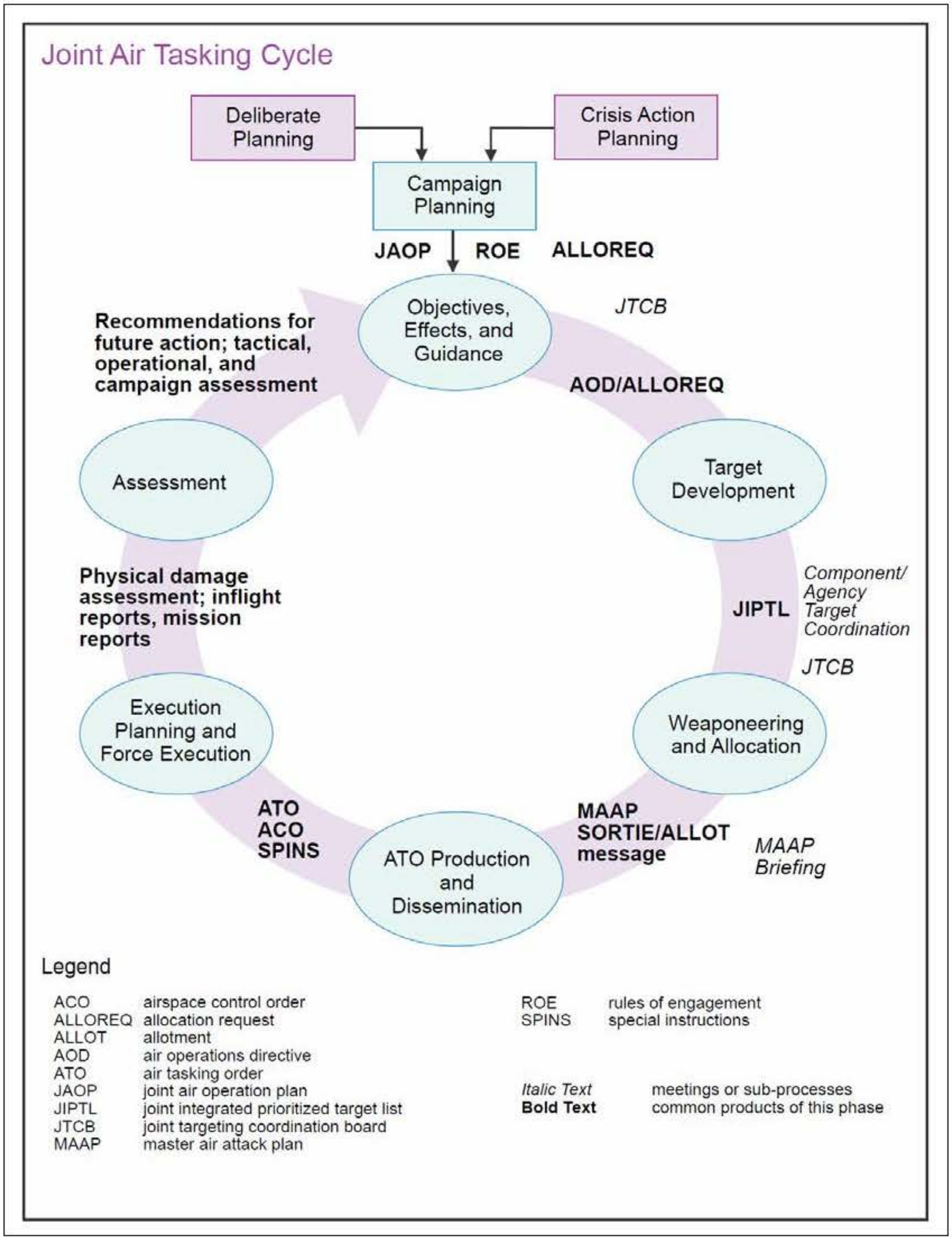

Figure 2.1: **Joint Air Tasking Cycle (JCS 2014).** An iterative 120-hour cycle for planners within the AOC to develop targets, allocate air assets, assign tasking, execute the missions, and assess the plan's performance. The cycle is accomplished by six divisions within the AOC and is synchronized across five separate ATOs simultaneously.

The Joint Air Tasking Cycle (see Figure 2.1) details the typical 120-hour cycle for target development and air assignment to the ATO, execution of missions, and assessment of results which then feeds the next cycle. Five divisions within the AOC conduct the decision making: strategy, combat plans, combat operations, intelligence, surveillance, and reconnaissance (ISR), and air mobility. The cycle starts with the strategy division, who formulate the air operations directive (AOD) to ensure that the guidance is in line with the JFC intent. The combat plans division then produces the joint integrated prioritized target list (JIPTL), and, upon approval of the JFACC, prioritizes the missions through the master air attack plan (MAAP) which initially assigns weapons-delivery platforms to targets from the JIPTL. The combat operations division produces the ATO and oversees its execution. Finally, the ISR and air mobility divisions conduct the post-execution assessment and determine logistical requirements of the cycle.

An ATO covers a 24-hour period so over the 120-hour Joint Air Tasking Cycle each of the five divisions are working on a different day. For example, the combat plans division develops targets for the JIPTL that will be executed on the ATO two days into the future. In this structured environment, deliberate planning is conducted on each of the targets to ensure that an appropriate combination of aircraft and weapons is available and assigned to produce the desired effects. Different combinations of weapon effects can be considered using weaponeering software to account for specific weapon release conditions against known target parameters. Additionally, this timeline allows for air assets to be pre-positioned, or for flights to be coordinated into a strike package in order to overwhelm an enemy force, if needed.

While this cycle accounts well for static targets that are developed in advance, the dynamic nature of the modern battlefield environment frequently results in the need to bypass the deliberate planning cycle as *pop-up*, or previously unknown, targets appear. The AOC typically assigns a proportion of available flights to “on-call” missions which allow them to handle pop-up targets that appear during execution. Some of these missions are alert aircraft which are assigned to a ready status at a local airfield. Others are assigned to fly to holding positions, as airborne alert flights, where they await real-time mission assignment. For both of these types of alerts, the aircraft are typically loaded with versatile, “jack-of-all-trades” weapons and systems loadouts. These loadouts are pre-planned to account

for various target types within the AOR that are determined to be typical targets through assessment of previous ATO execution and intel inputs. The real-time mission assignment of these on-call missions is done through a process known as dynamic targeting (DT).

The doctrinal goal of DT is to engage an incoming targeting opportunity and achieve desired effects within a 30 minute timeline. This goal sets a benchmark for low and medium threat environments, however, there is no benchmark for a dynamic target cycle in high threat environments because the current process cannot handle the coordination that must occur in that environment within a short enough timeline to be effective.

A DT event typically starts within the AOC combat operations division when intelligence is received of a fleeting opportunity to engage a priority target. Within the first few minutes, a condensed targeting process must occur to include locating the target as well as selecting an appropriate air asset and weapon combination from existing assets to engage. Standard doctrine dictates that if the combat operations division determine an alert aircraft is to be utilized then the call is made to launch and the aircraft is assigned to an appropriate C2 agency. Separately, if the determination is to utilize an asset which is already airborne, the C2 operator which is controlling the AOR where the target is located is then contacted and the C2 operator passed the responsibility of assigning the mission to aircraft under that operator's control. This thesis focuses on the decision making processes of the condensed timeline to enable the essential elements of the deliberate planning process, that lend themselves to automation, to be encapsulated given the known current laydown of available assets and weapons even in the presence of enemy threat ADs.

2.3 C2 Operator Role in Real-time Mission Assignment

The link between the AOC and the airborne assets is the C2 operator. The C2 operator performs deconfliction of assets, conducts real-time mission assignments, and provides critical threat updates to the aircrew. The C2 operator provides to the AOC status reports on current mission assignments as well as updates on missions that have been completed via mission reports (MISREPs). C2 operators are in constant communication with the airborne assets within their AOR and therefore are the clearinghouse for the most up-to-date asset, target, and threat information. As flights complete their missions they update the C2 operator with what weapons were employed and what the effects on the target were

20 December 2007 FM 3-09.32/MCRP 3-16.6A/NTTP 3-09.2/AFTTP(I) 3-2.6 103

Table 28. Recommended Target-Weapons Pairings for Ordnance

Targets	Recommended Ordnance
Artillery, AAA, Rocket Launcher: In the open	CBU-87/97/103/105, JSOW, GP bomb, GBU-39, JDAM, LGB (GBU- 10/12/16/24), Maverick, Hellfire, TOW, (E)GBU-15, AGM-130, 2.75" rockets (w/ M255E1/WDU-4A/A Flechette, M261, M299, M151), 30/ 40 mm gun
In revetment	CBU-97, GP bomb, GBU-39, JDAM, LGB (GBU-10/12/16/24), Maverick, Hellfire, 30 mm, (E)GBU-15, AGM-130, 2.75" rockets (w/ M261, M229, M151)
In covered position	GP bomb, JDAM, LGB (GBU-10/12/16/24), Maverick, Hellfire, (E)GBU- 15, AGM-130, 2.75" rockets (w/ M229, M151)
SAM Site / Surface-to-Surface Missile Site	HARM, CBU-87/97/103/105, JSOW, GBU-39, JDAM, Hellfire, GP bomb, LGB (GBU-10/12/16/24), TOW, (E)GBU-15, AGM-65/130/158, 20/25/30/40/105 mm, 2.75" rockets (w/ M261, M229, M151), SLAM-ER
Moving Targets	Maverick, Hellfire, Laser JDAM, GBU-12/51, 20/30 mm guns (strafe)

AGM – air-to-ground missile
AP – armor piercing
CBU – cluster bomb unit
CEM – combined effects munition
E – enhanced
GBU – guided bomb unit
GP – general purpose
HARM – high-speed antiradiation missile
HEI – high explosive incendiary
JDAM – Joint Direct Attack Munition
JSOW – joint stand-off weapon
LGB – laser-guided bomb
SFW – sensor-fused weapon
SLAM-ER – stand-off land attack missile – expanded range
TOW – tube-launched, optically tracked, wire guided
WCMD – wind corrected munitions dispenser

Figure 2.2: **JFIRE Recommended Target-Weapons Pairings for Ordnance (ALSA 2007).** This is an example of standard kneeboard pack information that is provided for in-flight weapon-target pairing recommendations. This page shows that for moving targets there are five recommended weapons, however, it does not indicate the expected performance of those individual weapons would be.

in addition to an updated on-station time for the flight. Applicable aspects of the MISREP information are then disseminated to the AOC.

The AOC passes approved missions to C2 operators for locations within their AOR. The C2 operators then pull upon their personal experience, or in-flight tools such as the JFIRE kneeboard pack (Figure 2.2), to determine which of the available assets that they will assign to complete the missions. However, these tools often provide overly general recommendations. The effectiveness of the assignment lies solely in how well the operator can assess the available information and apply his/her knowledge of the individual performance of available weapons, and weapon systems, against available missions.

While the current performance of C2 operators is limited, the most significant failure point of the existing process is when operators must account for multiple, dynamic SAM threats.

Determining assignments and routes for avoiding these threats is complicated, and significantly increases the time for the operator to arrive at assignment decisions. The first priority for C2 operators, upon detection of a new SAM threat, is to determine whether any flights are currently in danger from the threat. If this is the case, immediate direction to exit the threat area is provided to the flight(s). Then, the operator must decide which assignments have been affected by the presence of the threat and re-assign as required to avoid the threat.

In cases where high priority targets are covered by SAMs, unless expensive standoff weapons are available, there is usually no way to avoid the threat and prosecute the target. In these cases, the C2 operator must pair up flights carrying bombs with flights that have suppression of enemy air defenses (SEAD) capability. This further complicates the decision making process for C2 operators and, regardless of the priority of the mission, targets within SAM envelopes are often skipped in order to complete other missions which do not pose such challenges. In environments with multiple threats, the operational and tactical decision making process is currently done by a dedicated planning cell. The key elements of that process are included in the next section.

2.4 Dedicated Air Mission Planning for SAM Threats

Planning and executing a dedicated air mission against defended targets is an extremely challenging undertaking. This mission calls upon the broad set of skills for which aviators train and demands extensive planning in order to achieve the objectives with the lowest possible risk to the aircraft and aircrew. The planning cycle for such an event is often on the order of eight hours in which planners coordinate their individual specialties, under the leadership of the strike lead, to ensure that all objectives will be achieved while avoiding the risk from enemy threat systems.

A dedicated air mission planning cycle begins well before the planning team is assembled. The early stage of the cycle is where the assets are assigned by the ATO, the strike lead develops a rough sketch of his intent for the plan, and the intelligence specialists generate target folders for each of the missions. Because of the experience required to lead both the planning and execution of these events strike leads are typically senior squadron Commanding Officers, Executive Officers, and Department Heads that are designated to lead large packages of aircraft into combat by the Airwing Commander after demonstrating tactical prowess as well as the requisite leadership skills.

The ATO is utilized to assign aircraft to the strike mission, per the guidance of the JFACC or JFC. However, it is the mission of the strike lead to create the final attack plan and recommend any adjustments to the required assets as needed during the planning process. Target folders have either already been developed from previous planning cycles, been provided by the AOC, or must be quickly produced by the command's targeteering team. These target folders not only provide information about the target, but also contain recommendations on the types of weapons to employ in order to produce desired results.

Targeteering officers are specially trained to work with weaponeering software which estimate the effects from weapons employed upon targets that are built up within the software. The targeteer will match multiple weapons to the target via this software and produce a table of destruction probabilities by type of weapon which is then placed within the target folder. Frequently potential targets are designated and target folders are produced well before missions are assigned; in these cases the targeteer does not have the luxury of knowing the exact employment parameters (speed, altitude, etc,) of the aircraft and must use some generic parameters. Therefore, part of the air mission planning process is to determine a more accurate probability of target destruction based upon the specific release parameters for the specific mission and is typically completed a few hours into the planning cycle.

The planning cycle generally enables an hourly opportunity for planners to address issues that arise which adversely affect their breadth of planning. For instance, a route may enter the target area directly over a mountain because the enemy air defenses are weakest there, however, due to the elevation of the mountain the attacking aircraft's weapon system is unable to adequately acquire the target with sufficient time to successfully employ weapons, or the terrain may interfere with the trajectory of the weapon. In this case, the route may need to be adjusted to accommodate the target acquisition requirement which, in turn, may adversely affect the SEAD planning. Conversely, if a weapon which has a high probability of target destruction requires the attacking aircraft to approach closely to the target and the SEAD planning determines that it cannot support that distance into the SAM threat then the plan may need to be adjusted in order to accommodate a weapon with a higher standoff or the higher risk of losing aircraft must be accepted under the original plan.

Similar problems arise in planning cycles which are significantly shorter than the dedicated air mission planning. A subset of DT missions, TST events, are designed at eliminating

short-notice threats in environments where there is minimal threat from SAM systems, but occasions arise where tactical aircraft must be coordinated with SEAD elements and SAM threats must be minimized through both route adjustments for avoidance as well as strict coordination for suppression. These coordination efforts lack the diligence of a Strike planning process and must be generated using rules-of-thumb. If the route planning and weapon-to-target pairing were conducted prior to assignment, the need for the airborne assets to spend time generating the plan from rules-of-thumb would be alleviated, and provide the assigning units with a better understanding of how to effectively assign assets for overall mission success.

2.5 Challenges in Proposed Future Operations

Both the U.S. Navy and Defense Advanced Research Projects Agency (DARPA) have expressed interest in automated battlespace management aids, like the model developed in this thesis, in open source publications. The director of Integrated Fires for the Deputy Chief of Naval Operations for Information Dominance, Ms. Margaret Palmieri, wrote an article expressing the need for "tools that can assess the situation and recommend to decison makers – or when time constraints mandate, assign to combat systems – the best weapon target-pairs"(Palmieri 2014). DARPA is looking to industry for answers that will not only be capable of handling the complexity and scale of current operations but will also handle the further complexity of operations with distributed unmanned systems (see Figure 2.3) (DARPA 2014).

2.6 Automated Air Mission Planning

We propose a model (and associated pre-processing algorithms) that automate steps within the air mission planning cycle to streamline real-time pairing assignments. C2 operators have limited time with which to compare options when assigning missions. Our model takes the information that they already have and provides solutions which relieve them of that burden. This decision aid, in low and medium-threat environments, substantially outperforms the arbitrary 30 minute doctrine with an automated solution that seeks to eliminate targets within the shortest time possible and with the best assets available. Additionally, using this model provides C2 operators the information needed to be able to handle dynamic targeting (DT) missions in high-threat environments, an option that does not currently exist in the manual planning process.

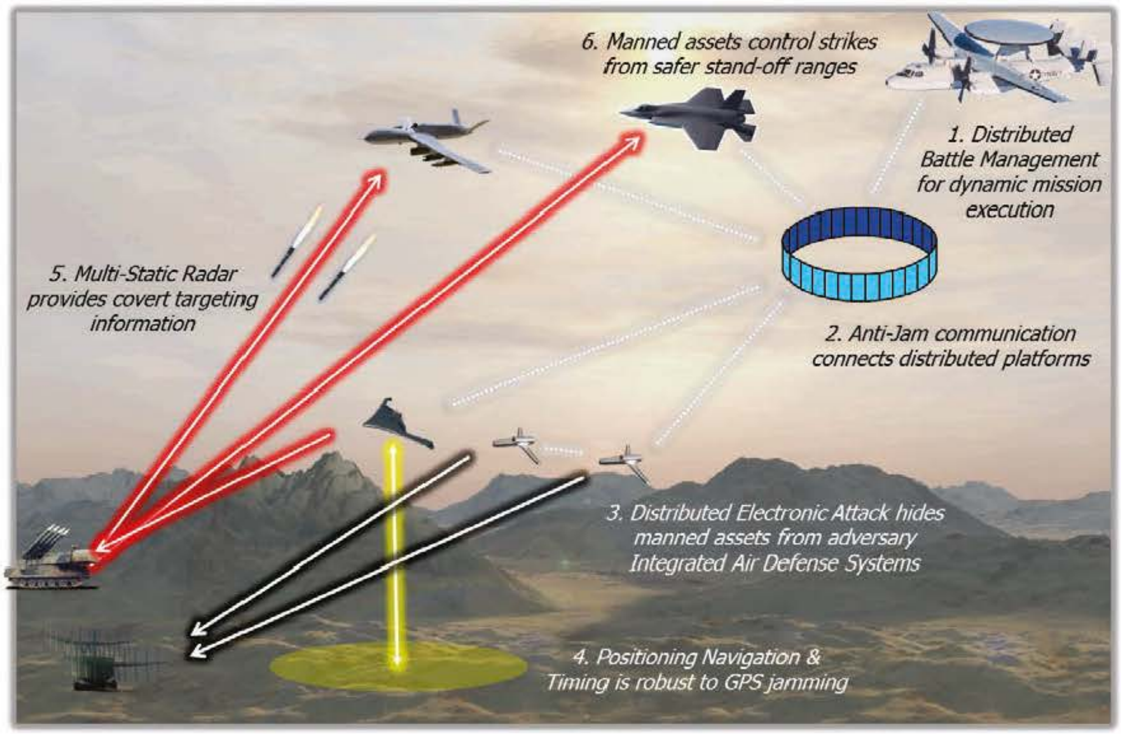

Figure 2.3: **Distributed Battle Management Complexity (adapted from DARPA (2014)).** Managing multiple, distributed systems in dynamic environments is complicated and requires automated decision aids. Proposed integration of systems, like those indicated in this figure, presents challenges to the aircrew who must quarter-back complex mission assignments.

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CHAPTER 3: Air Asset-to-Mission Assignment Model for High-Threat Environments

3.1 Introduction

This chapter formulates the asset-to-mission assignment problem, in the presence of threats, and develops the data pre-processing and post-processing algorithms required to formulate and solve instances of the problem based on available data regarding friendly and threat conditions within the battlespace.

The pre-processing algorithm (Section 3.2) (a) takes both static and dynamic inputs from the Excel graphical user interface (GUI), (b) enumerates the possible asset-to-mission assignments, and (c) screens out infeasible assignments based on great-circle route calculations. Next, the algorithm takes the latitude and longitude bounds of the operating area from the data and produces a grid overlay of the operating area which is then fed to the routing algorithm (Section 3.3), as well the aircraft, mission, and threat location data. The routing algorithm then generates minimum-risk routes for each feasible set of assignments (see Figure 3.1). A route is considered "minimum-risk" if the time spent within the effective range of the surface-to-air missile (SAM), or threat weapon engagement zone (WEZ), is minimized. Any assignment that contains a route that must enter a threat envelope is then processed to determine a "join-up" location, or decision point, for pairing with a suppression asset (see Figure 3.2). This new set of assignments is again processed with the same routing algorithm which takes each of the suppression asset locations and determines minimum-risk routes to each of the decision points.

After a route has been produced for each feasible assignment, the algorithm takes the distance calculations from the determined routes and converts them to expected time for completion based upon the aircraft speeds that are contained in the original input data. These timing calculations are then fed back into the pre-processing algorithm to screen the assignments down to the final feasible set of assignments. A "reward" value is calculated for each assignment accounting for the commander's priority and precendence of each mission, the

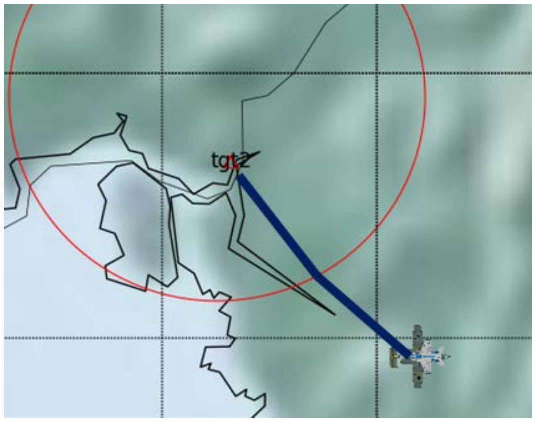

Figure 3.1: **Visual Depiction of Minimum-Risk Routing.** The blue line in this picture depicts minimum-risk routing for a flight prosecuting a target within a threat SAM WEZ. The goal is to reduce time spent inside the WEZ, indicated with a red circle, which is dependent on distance travelled and speed of the flight.

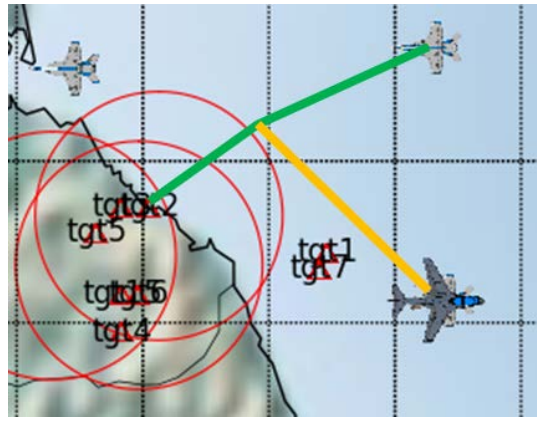

Figure 3.2: **Visual Depiction of Suppression Plan Routing.** The green line in this picture depicts reduced risk routing for a flight prosecuting a target within multiple threat SAM WEZs. The orange line depicts the routing for a SEAD suppression flight to join and stay outside of the threat while providing suppression.

probability of achieving the desired result, the effectiveness of the asset to that mission, the efficiency of asset use, and the survivability of the asset while conducting the mission. The optimal subset of the feasible assignments is then selected by solving a mixed-integer programming (MIP) formulation (Section 3.4). Finally, post-processing provides the user with the pairing assignment as well as recommended routing, expected time of completion, and overall probability of successful mission accomplishment. This chapter provides the formulation for each step we have developed for this model.

3.2 Pre-processing

The following pre-processing algorithm takes both static and dynamic input data and produces a set of possible assignments that meet initial feasibility conditions. The static data is a collection of information in lookup tables which do not change over the course of an operation (see Figure 3.3 (Static Data)). In comparison, dynamic data are those elements of information which are updated as flights, missions, and threats enter or exit the battlespace (see Figure 3.3 (Dynamic Data)). These input encompass the formulation of the algorithm as follows.

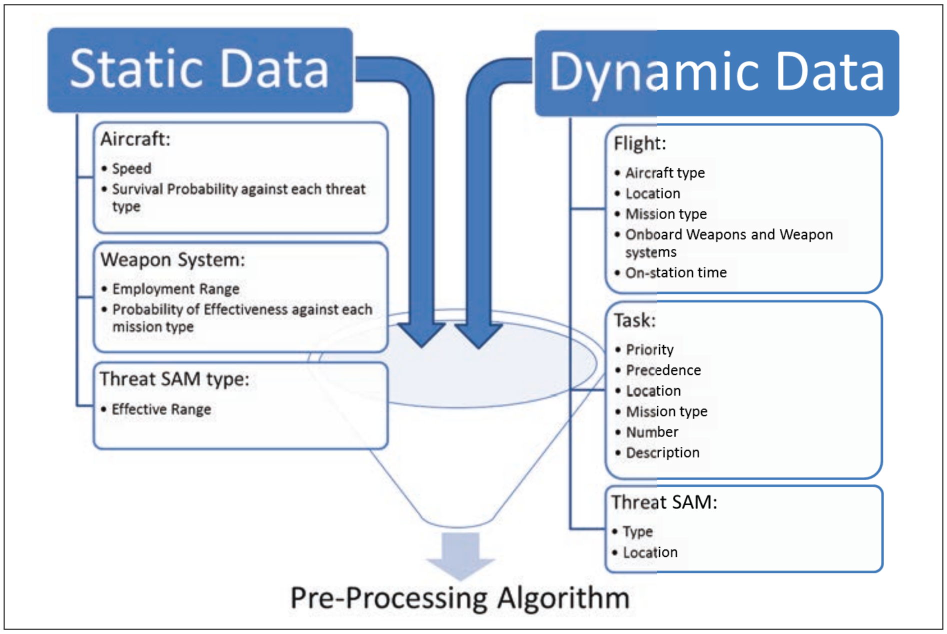

Figure 3.3: **Static and Dynamic Inputs.** The data for the pre-processing algorithms of the model take two forms. Static data, like performance information, is entered prior to the event. Dynamic data is updated by the operator as changes occur with regards to flights, targets, and threats.

3.2.1 Sets

$f \in F$	Flight of aircraft, identified by its designated callsign
$w \in W$	Weapon system type
$t \in T$	Target or Mission identification
$s \in S$	Suppression plan, identified by the suppression flight callsign, or by 'noSEAD' if no suppression plan is utilized or required (alias s2)
$SEAD \in F$	Subset of F that are threat suppression flights $S \equiv SEAD \bigcup \{`noSEAD'\}$
$(f,w,t,s) \in P \subseteq F \times W \times T \times S$	Assignment tuple representing a flight f utilizing weapon system w assigned to target t and suppression plan s, corresponding to a $feasible$ pairing (as defined below)

3.2.2 Data [units]

$priority_t$	Commander's priority for target t [reward units]
$precedence_t$	Requestor's precedence for target t [reward units]
$prob\_kill_{w,t}$	Individual probability of kill of weapon w against target t [probability]
$num\_weapons_{f,w}$	Number of weapons of type w in flight f [number of weapons]
$num\_targets_t$	Number of targets within target t [number of targets]
$playtime_f$	On-station time remaining for flight f [minutes]
$range_w$	Standoff employment range of weapon w [nautical miles]
$mission\_type_f$	Mission type of flight f [CAS, XINT, MEDVAC, etc]
$target\_type_t$	Mission type required by target t [CAS, XINT, MEDVAC, etc]
$speed_f$	Cruise speed of flight f [knots]
$gc\_distance_{f,t}$	Great-circle distance from current location of flight f to target t [nautical miles]
$gc\_time\_to\_target_{f,t}$	Calculated time for flight f to employ on target t using great-circle route distance [minutes]
$distance_{f,t}$	Transit distance from current location of flight f to target t while avoiding exposure to threats [nautical miles]
$time\_in\_WEZ_{f,w,t,s}$	Calculated effective time which flight f would spend in the threat Surface-To-Air WEZ employing weapon w against target t with suppression plan s [minutes]
$time\_to\_target_{f,t}$	Calculated time for flight f to employ on target t [minutes]
$distance\_dp_{f,t}$	Transit distance from current location of flight f to decision point for target t while avoiding exposure to threats [nautical miles]
$time\_to\_dp_{f,t}$	Calculated time for flight f to transit to decision point for target t [minutes]
$join\_time_{f,w,t,s}$	Calculated time required for flight f to join with suppression flight s against target t [minutes]

3.2.3 Calculated Data

$$
\begin{aligned}
gc\_time\_to\_target_{f,t} = &\quad 60 \times \left\lceil \frac{gc\_distance_{f,t}}{speed_f} \right\rceil \\
time\_to\_target_{f,t} = &\quad 60 \times \left\lceil \frac{distance_{f,t}}{speed_f} \right\rceil \\
time\_in\_WEZ_{f,w,t} = &\quad 60 \times \left\lceil \frac{dist\_in\_threat_{f,w,t}}{speed_f} \right\rceil \\
time\_to\_dp_{f,t} = &\quad 60 \times \left\lceil \frac{dist\_dp_{f,t}}{speed_f} \right\rceil \\
join\_time_{f,w,t,s \in SEAD} = &\quad max(time\_to\_dp_{f,t}, time\_to\_dp_{s,t})
\end{aligned}
$$

3.2.4 Selecting Feasible Assignments

Selecting the feasible set of assignments, P, is a three-step process. The first step screens assignments for feasibility based upon rough, point-to-point routing and compatability of mission types between flights and missions: if $gc\_time\_to\_target_{f,t} <= playtime$ and $mission\_type_f \in \{target\_type_t, \text{'any'}\}$, the pairing is considered feasible for the moment, otherwise it is permanently rejected.

This initial feasible set is fed to the routing calculation algorithm (Section 3.3) where minimum risk routes are produced for each feasible flight and target pairing. The pre-processing algorithm takes the routes and determines the transit time for each pairing as well as whether the assignment will require penetration of a known SAM WEZ, if so, $time\_in\_WEZ_{f,w,t}$ is calculated. These, more accurate, time calculations are then processed by the algorithm through a second pass of feasibility conditions to screen the feasible set.

In the second pass, the set P represents combinations of flight, weapon, and target without a suppression plan that meet the following feasibility conditions: $(f, w, t, \text{'}noSEAD') \in P$ if and only if: $time\_to\_target_{f,t} \leq playtime_f$, and $time\_in\_WEZ_{f,w,t} <= 10$ [minutes].

In the third, and final pass, any assignment within the feasible set is paired to a SEAD flight and added to the set, P, if $time\_in\_WEZ_{f,w,t} >= 0$ and a SEAD flight is available. A join lo-

cation is determined for these new pairings which is the closest grid location to the mission location along the path that is not within a SAM WEZ. These join points are enumerated with the locations of the paired SEAD flights and fed to the routing algorithm which computes minimum-risk routing to the join points. This information is added to the inputs for the pre-processing algorithm and $join\_time_{f,w,t,s}$ is calculated. The final feasibility check rejects any assignment where $s \in SEAD$ and $join\_time_{f,w,t,s} + time\_in\_WEZ_{f,w,t} <= \min(playtime_f, playtime_s)$. The algorithm then computes a *reward* for each pairing in the final feasible set which is the input for the optimization model.

3.2.5 Reward Value Calculation

The reward value calculated for each pairing in the feasible set, P, is a weighted combination of several measures of effectiveness that evaluate the commander's priority and precendence of the target, the flight's weapon perfomance on the target, the timeliness of execution based upon routing, and the reduction of risk based upon the effect of pairing with a suppression plan.

$$\begin{aligned} reward_{f,w,t,s} = \quad & (100 - (30 \times (priority_t - 1)) - precedence_t) \\ & \times (1 - (1 - prob\_kill_{w,t})^{num\_weapons_{f,w}/num\_targets_t}) \\ & \times 100 \times e^{(-.05 * time\_to\_target_{f,t})} \times e^{(-.01 * playtime_f)} \\ & \times e^{(-8.0 * (1 - surv_{f,t}) * time\_in\_WEZ_{f,w,t})} \end{aligned}$$

The first three coefficients come from the Rapid Air Strike Pairing (RASP) model as formulated by McLemore (2010). The aggregate of these first three coefficients provide a numerical value between 0 and $9,900$ with higher reward values indicating more desirable assignments. The first term ensures that the priority (values between one and three, lower being better) and precedence (values between one and 30, lower being better) are provided appropriate importance in the model. The second term influences the desirability of the assignment by increasing the reward for assignments which have a higher probability of success in completing the mission. The third term gives a higher reward for those assignments which complete the mission in the shortest amount of time as well as utilizing flights with the shortest playtimes, or available on-station times, that are feasible to complete the mission.

New to this model is the final term, $e^{-8.0*(1-surv_{f,t})*time\_in\_WEZ_{f,w,t}}$. Given calculated exposure time to the threat systems and tabulated survivability data, this term returns values between zero and one and rewards aircraft whose determined route minimizes the time spent within a threat WEZ as well as aircraft which are more survivable against the SAM system that poses a threat to the flight. We chose the value for the scaling factor, -8.0, to account for a significant decrease in the reward value as time spent in the SAM WEZ increases without overcoming the rest of the terms when the time is minimal.

The overall result of this calculation is a number between zero and 9,900, with larger values indicating more desirable assignments. The actual values of the reward coefficients have no direct interpretation; it is their values relative to each other that drive the model to choose better assignments. The individual factors can be modified, and the coefficients adjusted, to adapt to the commander's intent, but we have found that judicious choices of priority and precedence values provide a significant amount of flexibility to planners.

3.3 Minimum Risk Routing

The model's input for minimum risk routing includes a directed network representing a "gridding" of the airspace across the area of responsibility (AOR), with an additional set of nodes that represent aircraft start and end locations for their assigned missions. The routing algorithm uses this network to produce a shortest path route for each pairing. Where "shortest" is defined as the route that minimizes a combination of distance travelled and time of exposure to threat WEZs, which will contribute to the reward coefficients for the asset-to-mission assignment problem.

The aircraft, mission, and threat locations from the input data are initially processed to determine the latitude and longitude bounds of the operator's AOR. Then these bounds and an operator selected mesh-size value are processed to produce the directed network representing the airspace. An example of the network can be seen in Figure 3.4 where nodes contained within the grid are depicted with circles and colored arrows designate the directed arcs incident to an example node. Directed arcs connect each node horizontally, vertically, and diagonally to its eight adjacent, or *neighbor*, nodes. The size and spacing of the grid is controlled by the mesh-size parameter which is set to five nautical miles by

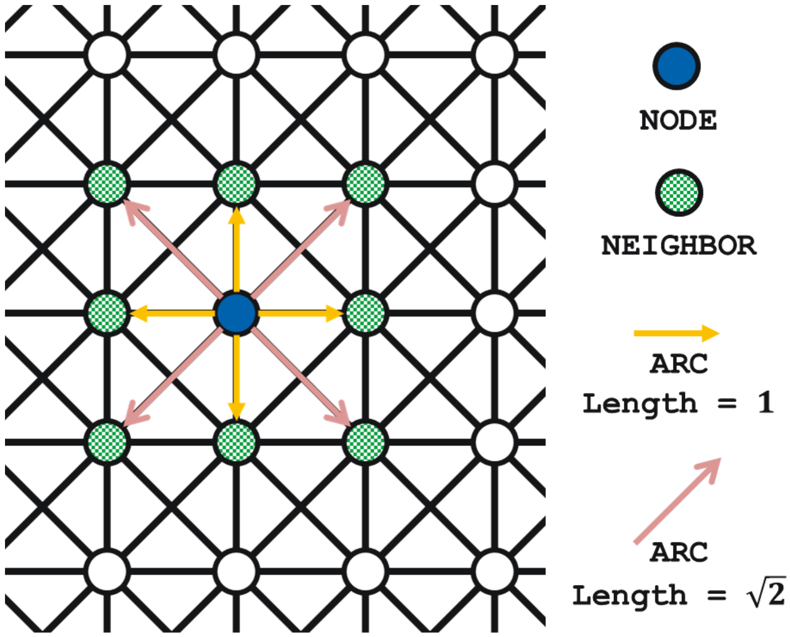

Figure 3.4: **Adjacency Grid.** This is a visual depiction of the overlay grid. The adjacent nodes, or *neighbor* nodes, are indicated in green with arc lengths between the nodes calculated using euclidean distance.

default. An increase of the mesh-size creates a less dense grid, and, decreasing it increases the number of nodes, which increases the routing precision, at the cost of increased pre-processing time.

3.3.1 Indexes

$node \in N$	Node in directed network (alias *current*)
$neighbor \in N$	Successor of *node*
$start \in N$	Start node
$end \in N$	Destination node

3.3.2 Data

$penalty_{node}$	Value associated to *node* for each threat that lies within its effective range from *node*
g_{node}	Total calculated distance travelled from *start* to *node*
h_{node}	Heuristic distance from *node* to *end* using euclidean distance
f_{node}	Combined distance from *start* to *node* and heuristic distance from *node* to *end*
$mesh-size$	Separation between horizontally and vertically adjacent nodes in the grid network
$g\_dist(node, neighbor)$	Calculated distance between *node* and *neighbor* which is equal to $mesh-size$ multiplied by the arc length between *node* and *neighbor*
$h\_dist(end, neighbor)$	Euclidean distance between *end* and *neighbor* multiplied by $mesh-size$

3.3.3 A* Algorithm

We use a modified form of the A* algorithm (Hart et al. 1968) (Algorithm 1) to find the shortest path from a *start* node to an *end* node within a directed network grid, where "shortest" is defined in terms arc; each arc (*i*,*j*) has a cost that is the sum of the travel distance from *i* to *j* plus any penalty assigned to *j* for being in one or more WEZs. The WEZ penalty is a value 10 times greater than the maximum expected distance travelled from two extreme corners within the network and is defaulted to $10,000$. The chosen default value assumes that the maximum distance travelled within typical AORs is $1,000$ nautical miles. Therefore, a successor node that lies within a SAM WEZ would incur a penalty of $10,000$ nautical miles onto any arcs from its predecessors in addition to the actual distance travelled along the arc.

Algorithm 1 A* MODIFIED PATH SEARCH ALGORITHM PSUEDOCODE

$OpenSet := \{start\}$
$ClosedSet := \emptyset$
$f_{start} := 0$
while $OpenSet \neq \emptyset$ **do**
  $current :=$ node with smallest value of f in $OpenSet$
  if $current = end$ **then**
    Stop search
  end if
  Remove $current$ from $OpenSet$
  for each $neighbor$ of $current$ **do**
    if $neighbor \in ClosedSet$ **then**
      Skip $neighbor$
    end if
    if $neighbor \in OpenSet$ **then**
      $g_{temp} := g_{current} + dist(neighbor, current) + penalty_{neighbor}$
      if $g_{temp} < g_{neighbor}$ **then**
        $g_{neighbor} := g_{temp}$
        $f_{neighbor} := g_{neighbor} + h_{neighbor}$
        $parent_{neighbor} := current$
      end if
    else
      $g_{neighbor} := g_{current} + g_{d}ist(neighbor, current) + penalty_{neighbor}$
      $h_{neighbor} := h_{d}ist(end, neighbor)$
      $f_{neighbor} := g_{neighbor} + h_{neighbor}$
      $parent_{neighbor} := current$
      Add $neighbor$ to $OpenSet$
    end if
  end for
  Add $current$ to $ClosedSet$
end while

3.4 Asset-to-Mission Assignment Model

The following defines the formulation for the optimization problem. The sets and reward values are the same as those defined in Section 3.2.1 and Section 3.2.3.

3.4.1 Decision Variables

$ASSIGN_{f,w,t,s}$	Binary Variable; 1 if flight f is assigned with weapon system w on target t with suppression plan s, 0 otherwise

3.4.2 Formulation

$$\underset{ASSIGN}{\text{MAX}} \sum_{(f,w,t,s)\in P} reward_{f,w,t,s} \times ASSIGN_{f,w,t,s} \tag{3.1}$$

$$\text{s.t.} \sum_{w,t,s} ASSIGN_{f,w,t,s} \leq 1, \qquad \forall f \in F \tag{3.2}$$

$$\sum_{f,w,s} ASSIGN_{f,w,t,s} \leq 1, \qquad \forall t \in T \tag{3.3}$$

$$\sum_{f,w,t} ASSIGN_{f,w,t,s} \leq 1, \qquad \forall s \in SEAD \tag{3.4}$$

$$\sum_{w,t,s2\in S} ASSIGN_{s,w,t,s2} \leq 1 - \sum_{f\neq s,w,t} ASSIGN_{f,w,t,s}, \forall s \in SEAD \tag{3.5}$$

$$ASSIGN_{f,w,t,s} \in 0,1, \qquad \forall (f,w,t,s) \in P \tag{3.6}$$

3.4.3 Discussion

The objective function (3.1) calculates the total reward from all assignments chosen. Constraint (3.2) ensures that each flight is only paired with one target, or mission. Constraint (3.3) ensures that each target, or mission, has only a single flight assigned to it. Constraint (3.4) ensures that the SEAD flights are only assigned suppression missions in support of a single flight pairing. Constraint (3.5) ensures that SEAD flights cannot be assigned to a mission if they are already supporting a suppression mission for another flight.

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CHAPTER 4: Computational Results

To validate the model as an automated decision aid for high-threat environments, we compare solutions from the model using a slightly modified scenario from that used by McLemore (2010). This scenario solution and an expanded scenario solution are carried out on a 2.2 GHz Core i7^{TM} HP ENVY^{TM} operating Windows 7^{TM}.

4.1 Test Scenario

The test scenario depicts notional threats and targets along the border between North and South Korea. Five flights of aircraft are awaiting assignments and the command and control (C2) operator has been passed three targets as well as three active SAM locations within the designated AOR (see Figure 4.3). Like the McLemore scenario, all data in both Figure 4.1 and Figure 4.2 are made up and are as close as possible to those in the previous scenario. This scenario does differ from the Mclemore scenario on two points: (1)Where one of the SAM sites was passed as a target, we leave the SAM off the target list and so are able to test the results with regards to SEAD pairing. (2)We change the mission type for each of the flights, except the EA-6B, to “any.” The purpose being to demonstrate the versatility the solutions our model provides. Decision makers at the air operations center (AOC) level utilize mission types as a means to communicate intentions for the flights to the C2 operators to help them limit the possibilities of assignments in real-time. With this model, all possibilities can quickly be assessed, eliminating the need for the AOC to be unnecessarily selective.

The tables pictured in Figure 4.1 are screen captures from the Excel GUI used to provide inputs to the model. The top table contains the particular flight information and contains the callsign, playtime (on-station time), mission type, aircraft type and number, location, and weapon system loadout. We utilize five different types of aircraft (A-10, F/A-18C, F-16, F/A-18F, and EA-6B) as well as a mix of six weapons (AGM-65E Laser-Guided Maverick, GBU-16 1,000 pound LGB, GBU-32 GPS-guided Joint Direct Attack Munition (JDAM), AGM-88 high-speed antiradiation missile (HARM), and the GAU 8 Avenger 30mm Gatling gun) as and three weapon systems (Litening and ATFLIR targeting pods and jamming

	Weapon Systems					LOCATION			Weapon System Loads							
Callsign	Status	Playtime	Mission	A/C Type	#	Waypoint	LAT	LONG	Load 1	#	Load 2	#	Load 3	#	Load 4	#
LONGHORN 31	available	120	any	A10	2	LA	372750N	1270600E	A65E	3	G16	2	Litening II	1	GAU 8 burst	2
TROJAN 13	available	15	any	FA18C	2	LA	372750N	1270600E	G32	2	ATFLIR	1				
COWBOY 41	available	45	any	F16	2	MIAMI	375610N	1282740E	G32	2	ATFLIR	1				
SPARTAN 23	available	25	any	FA18F	2	MIAMI	375610N	1282740E	G16	2	ATFLIR	2				
TARHEEL 38	available	60	SEAD	EA6B	1	MIAMI	375610N	1282740E	A88	2	Jamming Pod	2				

	Targets						COORDINATES	
TGT ID	Description	# Targets	Type	Status	Priority	Precedence	LAT	LONG
1	trucks moving	4	CAS	approved	1	10	382131N	1265411E
2	Tanks in Revetments	6	INT	approved	2	20	375005N	1263932E
3	cave	1	INT	approved	1	1	383203N	1274023E

Status	ID Number	Type	Latitude	Longitude	Range
Active	SA1	SA-6	382923N	1273128N	13
Active	SA2	SA-2	382228N	1275815N	23
Active	SA3	SA-2	375714N	1263741N	23

Figure 4.1: **Test Scenario Dynamic Data.** In this scenario, five flights are await assignment from the C2 operator. The operator has been tasked with assigning three missions and is aware of three SAM threat systems within the AOR. For example, SPARTAN 23, a flight of two F/A-18F Super Hornets, has 25 minutes of on-staion time, or "playtime", with a total of two GBU-16 LGB and an ATFLIR pod which provides the Laser to guide the bombs. Target 1, is a set of four moving trucks with a commander's priority 1 and precendence 10. SA3 is a SAM site consisting of an SA-2 Guideline and it's associated radar which has an effective range of 23 nautical miles.

pods for the EA-6B). The middle table contains target information for the three scenario targets; trucks moving on a road, tanks in revetments, and a high-value individual in a cave. Their identification number, number of target, mission type, priority, precedence, and locations are also included. The bottom table contains the threat SAM information to include identification number, type of system, location, and effective range that is pulled from the static data.

The two tables pictured in Figure 4.2 are screen captures of a reduced set of the large lookup tables of static data within the data. The top table contains speed data for each of the five aircraft as well as survivability data for each aircraft and SAM combination in the scenario. The lower table contains weapon employment ranges for each weapon, or weapon system, as well as probability of kill, or effectiveness, for each weapon and target combination in the scenario. All of the data in these two tables are made up and, at times, purposefully adjusted to demonstrate particular aspects of the model.

An embellished image of the GUI provided to the operator is provided in Figure 4.3 and depicts the scenario aircraft, target, and threat locations. The red circles represent threat ranges for two SA-2s and a single SA-3. Model results from this scenario (see Figure 4.4) provide a recommendation to assign the FA-18F flight to the moving trucks, using their

Aircraft Performance / Survivability Table			
Weapon System Type	Speed	SA-2	SA-3
FA18C	350	0.7	0.9
FA18F	340	0.7	0.9
F16	400	0.7	0.9
A10	250	0.7	0.9
EA6B	350	0	0

Weapon Employment Performance Table				
Weapon Range	Weap-Tgt Prob_k	Trucks (moving)	Cave	Tanks in Revetments
5	A65E	80%	20%	60%
40	A88	0%	0%	0%
0	G16	90%	60%	70%
0	G32	0%	30%	50%
20	Litening II	0%	0%	0%
30	ATFLIR	0%	0%	0%
0	GAU 8 burst	80%	0%	0%
80	Jamming Pod	0%	0%	0%

Figure 4.2: **Test Scenario Static Data.** The static data for this scenario contains speeds for each aircraft as well as survivability ratings for the aircraft against the known threats. The weapon employment data contains both standoff ranges and probabilities of success of using the weapons on the specific targets available. For example, an F/A-18F Super Hornet will transit at 340 kts and has a 0.7 and 0.9 probability of survival against the SA-2 and SA-3 systems, respectively. A GBU-16 LGB has no standoff capability and 90%, 60%, and 70% probability of successfully destroying moving trucks, a cave, or tanks in revetments, respectively.

GBU-16s; the F-16 flight to the cave, using their GBU-32s and supported by SEAD coverage from the EA-6B flight; and the FA-18C flight to the tanks, using their GBU-32s. This leaves the A-10 flight without an assignment and available for other missions that may arise.

In Table 4.1, we provide the parameters and reward coefficients for each of the 19 feasible assignment pairings in this scenario. There are six assignment pairings in the table that have the EA-6B providing SEAD support due to threat for SAM attack in the target areas for those assignments, which can be identified by noting that the $time\_in\_WEZ_{f,w,t}$ for that assignment is greater than zero. Each assignment with those values greater than zero and "noSEAD" for its suppression plan has an alternate assignment with "TARHEEL 38" with the exception of "SPARTAN 23" and "TROJAN 13." In these cases, the F/A-18F and F/A-18C flights do not have enough on-station time to wait for the EA-6B flight to join up and coordination time required for the assignment and were therefore eliminated.

The reward coefficients from the assignments, which were selected in the solution, are highlighted in the table. The largest reward value, of 245.14, corresponds to the F/A-

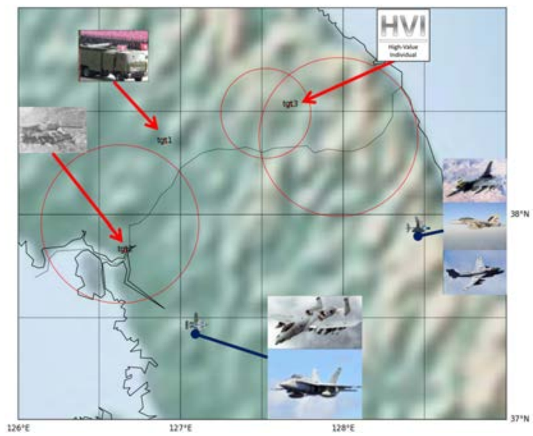

Figure 4.3: **Visual Depiction of Test Scenario.** This picture is an embellished screen capture from the model prior to assignment with the flights, targets, and threats from the scenario. The red circles represent SA-2 and SA-3 SAM effective ranges. The friendly aircraft are in holding, awaiting mission assignment against targets depicted by red arrows.

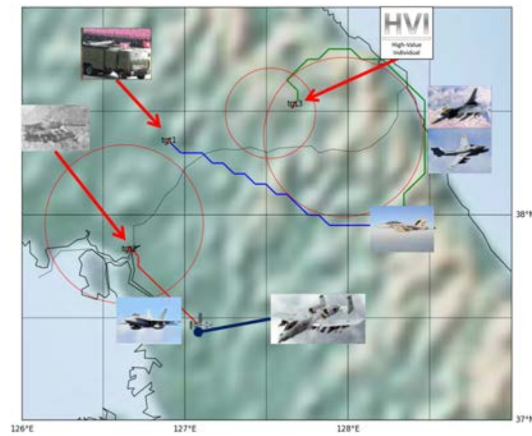

Figure 4.4: **Test Scenario Routes as derived from Solution.** This picture is an embellished screen capture from the model after mission assignments and routing have been assigned. The green line depicts the route for the F-16 flight, paired with the EA-6B flight for SEAD protection, against the cave target. The blue line depicts the route for the F/A-18F flight against the moving trucks. The red line depicts the F/A-18C flight against the tanks in revetments. The A-10 flight remains in hold awaiting further mission assignments.

18F flight targeting the moving trucks with their GBU-16 LGBs. This target is a high priority, GBU-16 have the highest effectiveness probability against the trucks, it can be accomplished within 15 minutes which is an efficient use of the flight's playtime, there is no SAM threats in the target area, and the route for the assignment avoids all known threats which all makes sense as to why this assignment received the highest reward value.

The next highest reward value, of 27.07, corresponds to the F-16 flight targeting the cave with their GBU-32 JDAMs and includes the use of the EA-6B flight for SEAD support. Without that support the reward value for this assignment would be 0.0069 due to roughly 3.5 minutes of threat exposure during employment in the target area. The route for this assignment (see Figure 4.4 green route) takes the flight around the east SA-2 and approaches the target from the north. From the picture it is easy to see that this route reduces the risk to the attacking aircraft for this assignment.

	LONGHORN 31 GAU 8 burst tgt1 noSEAD	LONGHORN 31 A65E tgt1 noSEAD	LONGHORN 31 A65E tgt2 noSEAD	LONGHORN 31 A65E tgt2 TARHEEL 38	LONGHORN 31 A65E tgt3 noSEAD	LONGHORN 31 A65E tgt3 TARHEEL 38	LONGHORN 31 G16 tgt1 noSEAD	LONGHORN 31 G16 tgt2 noSEAD	LONGHORN 31 G16 tgt2 TARHEEL 38
$priority_t$	1	1	2	2	1	1	1	2	2
$precedence_t$	10	10	20	20	1	1	10	20	20
$prob\_kill_{w,t}$	0.8	0.8	0.6	0.6	0.2	0.2	0.9	0.7	0.7
$num\_weapons_{f,w}$	2	3	3	3	3	3	2	2	2
$num\_targets_t$	4	4	6	6	1	1	4	6	6
$time\_to\_tgt_{f,t}$	14.5	13.3	6.6	6.6	26.3	26.3	14.5	7.8	7.8
$playtime_f$	120	120	120	120	120	120	120	120	120
$survivability_{f,w,t,s}$	1	1	0.7	1	0.7	1	1	0.7	1
$time\_in\_WEZ_{f,w,t}$	0.0000	0.0000	7.1859	7.1859	2.5165	2.5165	0.0000	9.5859	9.5859
commander weight	90	90	50	50	99	99	90	50	50
weapons weight	0.55279	0.70093	0.36754	0.36754	0.48800	0.48800	0.68377	0.33057	0.33057
timing weight	0.00030	0.00032	0.00044	0.00044	0.00016	0.00016	0.00030	0.00042	0.00042
survival weight	1.00000	1.00000	0.00000	1.00000	0.00238	1.00000	1.00000	0.00000	1.00000
REWARD	0.014841	0.019982	0.000000	0.008098	0.000019	0.007964	0.018358	0.000000	0.006859

	LONGHORN 31 G16 tgt3 noSEAD	LONGHORN 31 G16 tgt3 TARHEEL 38	SPARTAN 23 G16 tgt1 noSEAD	SPARTAN 23 G16 tgt2 noSEAD	SPARTAN 23 G16 tgt3 noSEAD	TROJAN 13 G32 tgt2 noSEAD	COWBOY 41 G32 tgt2 noSEAD	COWBOY 41 G32 tgt2 TARHEEL 38	COWBOY 41 G32 tgt3 noSEAD	COWBOY 41 G32 tgt3 TARHEEL 38
$priority_t$	1	1	1	2	1	2	2	2	1	1
$precedence_t$	1	1	10	20	1	20	20	20	1	1
$prob\_kill_{w,t}$	0.6	0.6	0.9	0.7	0.6	0.5	0.5	0.5	0.3	0.3
$num\_weapons_{f,w}$	2	2	2	2	2	2	2	2	2	2
$num\_targets_t$	1	1	4	6	1	6	6	6	1	1
$time\_to\_tgt_{f,t}$	27.5	27.5	14.5	17.0	17.1	5.6	14.5	14.5	14.6	14.6
$playtime_f$	120	120	25	25	25	15	45	45	45	45
$survivability_{f,w,t,s}$	0.7	1	1	0.7	0.7	0.7	0.7	1	0.7	1
$time\_in\_WEZ_{f,w,t}$	4.9165	4.9165	0.0000	7.0484	4.0536	6.8471	5.9912	5.9912	3.4456	3.4456
commander weight	99	99	90	50	99	50	50	50	99	99
weapons weight	0.84000	0.84000	0.68377	0.33057	0.84000	0.20630	0.20630	0.20630	0.51000	0.51000
timing weight	0.00016	0.00016	3.98350	3.50556	3.48311	16.85922	0.53901	0.53901	0.53607	0.53607
survival weight	0.00001	1.00000	1.00000	0.00000	0.00006	0.00000	0.00000	1.00000	0.00026	1.00000
REWARD	0.000000	0.012910	245.142462	0.000003	0.017249	0.000013	0.000003	5.559837	0.006935	27.066262

Table 4.1: **Test Scenario Calculated Parameters.** This table shows the reward coefficients and the values used to derive them for each feasible pairing within the scenario. The weight values take the values from the upper portion of each column and follows the *reward* formulation Section 3.2.3. The weights are multiplied together to achieve the reward for each assignment.

With only target #2 (tanks in revetments) left unassigned, of the remaining two flight's reward values, for assignments including this target, the F/A-18C flight has the higher value with 0.000013. Although this is a recommended assignment from the solution, the C2 operator should still make an assessment of whether or not to accept this assignment recommendation based upon such a low reward value. In this case, the assignment would pair the F/A-18C flight to employ their GBU-32 JDAMs on the tanks in revetments, however, this would require the aircraft to spend almost seven minutes inside an SA-2 WEZ without SEAD coverage. It would be prudent for the C2 operator to accept the first two recommendations and either hold the A-10 and F/A-18C flights for further assignments, or release them to another C2 agency.

We compare these results to the scenario results from McLemore (2010). While the pairing of the F/A-18F flight to the moving trucks remains the same, our model differs in that it assigns the EA-6B flight to provide SEAD support for the F-16 flight in targeting the cave which was the commander's highest priority and precedence target. Where our model recommends an assignment for the tanks, the added risk information is exceptionally valuable in providing the C2 operator precisely the information needed to make the right decision and pass up on the target until the threat can be suppressed and the friendly forces will remain more survivable.

Our pre-processing algorithms are written in Python 2.7, and the optimization model is formulated in General Algebraic Modeling Software (GAMS) and solved using the IBM ILOG CPLEX solver. After generating all of the feasible reward values, the resulting formulation has 12 constraints and 39 variables, 38 of which are binary, and solves in less than a second. The pre-procesing algorithms solve in 2.93 seconds for a solution with grid mesh size of 3 nautical miles. The additional computing time to create the provide pictures increased the scenario run time to a total of 7.53 seconds.

4.2 Expanded Test Scenario

For an expanded test scenario again we utilize a hypothetical conflict on the Korean Peninsula. In this case 35 flights await assignment for 18 approved targets under the protection of multiple SAM systems. This optimization model has 56 constraints and 1,961 variables, 1,960 of which are binary, and solves in less than a second. The overall solve time for this scenario is 2 minutes and 1.5 seconds without producing a picture and 2 minutes and 11.9 seconds with a picture, with a mesh size of 3 nautical miles is used for the overlay grid. Adjusting the mesh size to 5 nautical miles increases the run times to 22.1 seconds without producing a picture and 28.2 seconds with.

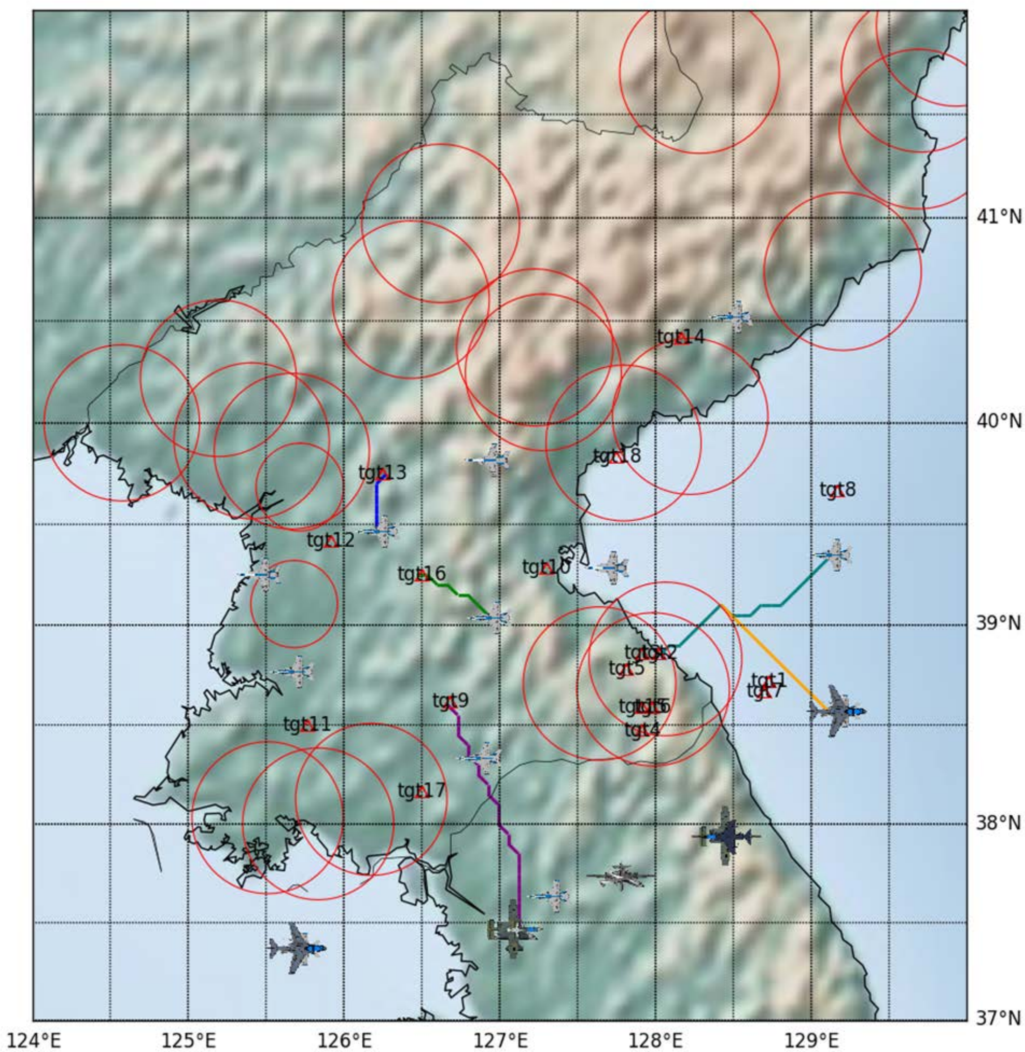

Figure 4.5: **Visual Depiction of Expanded Scenario.** This picture depicts the flight and target locations as well as the effective ranges (red circles) of each of the threats from the expanded scenario. Only five of the full nineteen routes are depicted for simplicity. The green (mission flight) and orange (SEAD flight) routes are used by the paired flights for threat mitigation. The other three routes are used by flights that are not entering known SAM WEZs and, therefore, do not have SEAD flights paired with them.

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CHAPTER 5:
Conclusions and Opportunities

5.1 Summary

Automated decision aids, such as the model we developed, are required to fix the current, inefficient system of assigning aircraft to missions in dynamic threat environments. We have shown that we can produce results that align with current doctrine much faster and more consistently than existing manual processes. The model solutions contain information critical to helping assess the effectiveness of the assignment as well as the survivability of the force for forward positioned command and control (C2) operators and air operations center (AOC) level decision makers. The manual decision making steps to account for the presence of enemy air defense (AD) systems hinder real-time mission assignments; however, aided with this model, air assets can be more effective in responding to significant time-limited opportunities to meet the objectives of the joint force commander (JFC).

5.2 Future Developments

The next step toward acceptable and incorporation of this model lies in test and evaluation. We have already approached the training department at Naval Strike and Air Warfare Center (NSAWC), NAS Fallon, NV, to incorporate the model into large-scale training events. This opportunity is intended to test the efficacy of the model in realistic scenarios that Naval Carrier Airwings undergo during pre-deployment work-up periods. These scenarios are similar in scale to the expanded test scenario we discussed (Section 4.2) and will include actual performance data vice the notional test data that has so far been used.

Our assignment model is a network flow problem, and could be solved with appropriate algorithms that could be incorporated directly into the Python code. This would provide a slight speed-up, but would also simplify installation requirements by eliminating the need for commercial software.

Our model has several other areas of development to include the incorporation of Air-to-Air threats, interfacing with Joint Tactical Information Distribution System (JTIDS),

accounting for coordinated routes with large-force strikes, and investigating the capability of the model for decision making with distributed unmanned systems.

The model currently handles AD threats from surface based surface-to-air missile (SAM) systems which are generaly far slower than enemy air threats. Incorporating the speed-of-advance of threat air assets would require timing adjustments of the threat range for the aircraft as routes are developed.

The current model still requires manual inputs through the provided Microsoft Excel™ GUI, however, this information could be populated more rapidly through the use of JTIDS information that is already shared between airborne platforms. The incorporation into JTIDS would also afford higher accuracy in location information as well as further reduce the task-loading of the C2 operator.

Large-force dedicated air strikes require coordinated routing of individual elements to ensure that the cumulative result of the package, as a whole, is near-simultaneous delivery of weapons. Future adaptations of the model, which account for this timing element, could provide the planners of these missions an automation tool for both plan development and analysis of alternatives which are not currently available to them.

Future incorporation of unmanned aerial vehicles as force multipliers in the battlespace would require a significant task-load to the manned assets in assigning each of the distributed platform's individual missions. This model could be adapted to be run on each platform where this assignment could be completed automatically, given that they all were provided the same inputs. The development effort would be to ensure that all of the data is sufficiently shared among the air assets so that the results remain consistent. The possibility of enemy network denial efforts could result in some of the distributed assets only receiving a portion of the data. Additionaly analysis for results based on incomplete inputs would be beneficial.

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